

Perspectives on Higgs Boson and Supersymmetry

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We review the recent discovery of the Higgs like particle at ~ 125 GeV and its implications for particle physics models. Specifically the implications of the relatively high Higgs mass for the discovery of supersymmetry are discussed. Several related topics such as naturalness and supersymmetry, dark matter and unification are also discussed.

Keywords: 125 GeV Higgs; Supersymmetry; Dark Matter, Unification.

I. INTRODUCTION

Using the combined 7 TeV and 8 TeV data, the ATLAS [1] and CMS [2] Collaborations find a signal for a Higgs like boson as follows: ATLAS Collaboration finds a signal at a mass of $126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})$ GeV at the 5.0σ level while CMS Collaboration finds a signal at $125.3 \pm 0.4(\text{stat}) \pm 0.5(\text{sys})$ GeV at the 5.0σ level. While there is the general belief that the observed particle is the long sought after Higgs boson [3–5] of the electroweak theory [6, 7], its properties still need to be experimentally established. Assuming it is a Higgs boson then its mass fits very well in the supergravity grand unification model with radiative breaking of the electroweak symmetry (SUGRA) [8–12] which predicts the Higgs boson mass to be less than 130 GeV [13–16] (for a previous review see [17]). Also the analysis within SUGRA model shows that the high mass of the Higgs boson implies that the CP odd Higgs boson mass $m_A > 300$ GeV and so one is in the decoupling limit (see also Ref. [18]). Of course as mentioned above one still needs to experimentally establish the spin and CP properties of the boson. Since the observed boson does decay into two photons, the Landau-Yang theorem [19] forbids the particle to have spin one, but it could be spin 0 or spin 2. If it were a spin zero particle, which is most likely the case, one still needs to establish its CP properties, i.e., the particle could be CP even or CP odd. The spin and CP properties can be established by an analysis of data using the processes $pp \rightarrow h^0 \rightarrow ZZ \rightarrow l_1 \bar{l}_1 l_2 \bar{l}_2$ and $pp \rightarrow h^0 \rightarrow W^+ W^- \rightarrow l^+ l^- \nu \bar{\nu}$ (see, e.g., [20] and [21] and the references therein). However, even after its spin and CP properties are established further work is required to identify the observed particle as the Higgs boson [3–5, 22] which is responsible for the breaking of the electroweak symmetry and generating masses for the ordinary quarks and leptons via spontaneous breaking.

Thus, for example, if the discovered boson was indeed a Higgs boson of the Standard Model electroweak theory, then its couplings to fermions and to dibosons will have the form $L_{h^0 A \bar{A}} = -\frac{m_f}{v} h^0 f \bar{f} - \frac{2M_W^2}{v} h^0 W^\mu W_\mu - \frac{M_Z^2}{v} h^0 Z^\mu Z_\mu + \dots$. A hint of new physics will emerge from deviations of the Higgs couplings from the above predictions. Thus one may define the ratio $R_{h^0 A \bar{A}} = g_{h^0 A \bar{A}}^{\text{BSM}} / g_{h^0 A \bar{A}}^{\text{SM}}$, and one can parameterize $R_{h^0 A \bar{A}}$ as follows $R_{h^0 A \bar{A}} = 1 + \Delta_A$, where any deviation from the standard model are encoded in Δ_A . Specifically one would need to experimentally determine several couplings such as $h\bar{b}b$, $h\bar{t}t$, $h\tau\bar{\tau}$, hWW , hZZ , $h\gamma\gamma$, $hZ\gamma$ (see, e.g., Ref. [23]). There are some hints of deviations from the Standard Model prediction in the $\gamma\gamma$ channel. Thus the CMS and ATLAS Collaborations give [1, 2]: $R_{\gamma\gamma} \equiv \hat{\mu} \frac{\Gamma(h \rightarrow \gamma\gamma)_{\text{obs}}}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}} = 1.8 \pm 0.5$ (ATLAS), 1.6 ± 0.4 (CMS), where $\hat{\mu} \equiv \frac{\sigma(pp \rightarrow h)_{\text{obs}}}{\sigma(pp \rightarrow h)_{\text{SM}}} = 1.4 \pm 0.3$ (ATLAS), 0.87 ± 0.23 (CMS). Now the $\gamma\gamma$ final state in the decay of the Higgs boson arises at the loop level from the $W^+ W^-$ in the loop and from the $t\bar{t}$ in the loops. A part of the W-loop contribution, which is the larger of the two contributions, is cancelled by the t-loop contribution. Additional light particles are needed in the loop to produce a significant correction and several works have appeared along these lines in the literature [24–31]. However, there is also the possibility that the observed excess is in fact a consequence of just the QCD uncertainties [32]. It is estimated that at LHC14 with an integrated luminosity of 3000fb^{-1} one will be able to measure the couplings of the Higgs with fermions and with dibosons with an accuracy in the range 10-20% [33] while at ILC at $\sqrt{s} = 1$ TeV and an integrated luminosity of 1000fb^{-1} one should be able to measure the couplings to about 5% accuracy [33]. An observation of any significant deviation will be of considerable interest in the exploration of new physics beyond the Standard Model.

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II. HIGGS BOSON AND SUPERSYMMETRY

In the Standard Model the Higgs boson mass can have a very wide range. Thus prior to the LHC measurements, the Higgs boson mass was constrained on the lower side by the LEP data and on the upper side by constraints of unitarity [34, 35]. Inclusion of stability of the vacuum provides further constraints. The analysis of vacuum stability is very sensitive to the next to leading order corrections and to the top mass. Very recently an analysis based on next-to-next -leading order (NNLO) correction requires that $m_h > 129.4$ GeV for the vacuum to be absolutely stable up to the Planck scale [36]. This result argues that the Higgs boson mass at ~ 125 GeV will require new physics if one wants vacuum stability up to the Planck scale (see, however, [37, 38]). Several suggestions have been made regarding how one may stabilize the vacuum up to the Planck scale (see, e.g., Refs [39, 40]). However, such models would still be subject to the large corrections to the Higgs boson mass, i.e., $m_h^2 = m_0^2 + O(\Lambda^2)$ where Λ is the cutoff which could be $O(M_G)$ where $M_G \sim 10^{16}$ GeV is the GUT mass, requiring a fine tuning in m_h^2 to 1 part in 10^{28} . Supersymmetry avoids this large fine tuning problem and at the same time it does not suffer from the problem of vacuum instability.

Now in supersymmetric theories the Higgs boson mass is predicted to be less than M_Z [41] and one needs loops corrections to lift the mass above M_Z . It was predicted that with inclusion of the loop corrections the Higgs boson mass for the mSUGRA (sometimes referred to as CMSSM) case [8–11] the Higgs boson mass lies below around ~ 130 GeV [13, 15, 16]. Thus it is quite remarkable that the Higgs boson mass eventually ended up just below the upper limit predicted by mSUGRA. Now getting the Higgs boson as high as around ~ 125 GeV requires an optimization of the loop correction. Thus the largest correction to the Higgs boson mass arises from the top-stop sector and is given by [42, 43] $\Delta m_{h^0}^2 \simeq \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{M_S^2}{m_t^2} + \frac{3m_t^4}{2\pi^2 v^2} \left(\frac{X_t^2}{M_S^2} - \frac{X_t^4}{12M_S^4} \right) + \dots$. Here M_S is the average stop mass, $v = 246$ GeV (v is the Higgs VEV), and X_t is given by $X_t \equiv A_t - \mu \cot \beta$ where μ is the Higgs mixing parameter and $\tan \beta = \langle H_2 \rangle / \langle H_1 \rangle$ where H_2 gives mass to the up quarks and H_1 gives mass to the down quarks and leptons. The maximization of the loop correction occurs when $X_t \sim \sqrt{6}M_S$ and achieving a Higgs boson mass of size ~ 125 GeV requires A_t/M_S to be sizable. Thus one finds that the ~ 125 GeV Higgs boson leads to restrictions on model building [30, 44–64]. It should, of course, be clear that in the above analysis we are not discussing global supersymmetry since breaking of supersymmetry is difficult in globally supersymmetric theories. Further, in globally supersymmetric theories one cannot cancel the vacuum energy and we need to work in the framework of local supersymmetry which requires inclusion of gravity [65, 66]. Thus within the supergravity unified framework one can obtain a viable breaking of supersymmetry as well as arrange for the vacuum energy to cancel [8–10]. Recently mechanisms for small vacuum energy have been discussed [67] within a class of string models such as, e.g., [68, 69].

A. Naturalness and supersymmetry

As discussed above supersymmetry provides a natural solution to the big hierarchy problem, i.e, a natural cancellation between the quark loops and squark loops that evades the need for a cancellation of 1 part in 10^{28} GeV. However, breaking of the electroweak symmetry induced by soft parameters appears to bring in another smaller hierarchy or the so called little hierarchy problem. Thus the electroweak symmetry breaking has the form $\mu^2 = -\frac{1}{2}M_Z^2 + [(m_{H_1}^2) - (m_{H_2}^2) \tan^2 \beta] / (\tan^2 \beta - 1)$, and if the Higgs masses and μ have sizes in the TeV region, then a significant cancellation is needed to arrange them to cancel so that M_Z has the size that is seen experimentally. It turns out, however, that there exist regions in the parameter space of SUGRA models where the Higgs masses can get large while μ remains small. This regime of radiative breaking is the Hyperbolic Branch (HB) [70–74]. Now HB has recently been classified [75] and shown to contain Focal Points (FP) [76], Focal Curves (FC) and Focal Surfaces (FS). Focal Points [76] are those regions where m_0 can get large while μ remains small, Focal Curves are those regions where (m_0, A_0) (the asymptotic form of this focal curve gives $|A_0/m_0| = 1$ [77]) or $(m_0, m_{1/2})$ can get large while μ remains small, and Focal Surfaces are those where $m_0, A_0, m_{1/2}$ can all get large while μ remains small. It turns out that the data from the LHC points to most of the parameter space consistent with all constraints lying on either Focal Curves or Focal Surfaces. The central point of the HB branch is that one can have natural TeV size scalars if they lie on HB. In the profile likelihood analysis using the LHC data one finds that the scalars are typically heavy, i.e., in the TeV region, and the CP odd Higgs mass is greater than 300 GeV [14], which implies that one is in the decoupling limit [78, 79] which is defined so that $\cos^2(\beta - \alpha) < 0.05$, where α is the mixing angle between the two CP-even Higgs bosons of MSSM. Another corroborating evidence that one is in the decoupling limit comes from the $B_s^0 \rightarrow \mu^+ \mu^-$ branching ratio being very close to the SM value since the supersymmetric correction to this process proceeds by the exchange of the Higgs bosons in the direct channel [80–86]. Thus LHCb gives $Br(B_s^0 \rightarrow \mu^+ \mu^-) < 4.5 \times 10^{-9}$ while the standard model result is $Br(B_s^0 \rightarrow \mu^+ \mu^-) \sim 3.2 \times 10^{-9}$ which shows that the supersymmetric contribution is rather small which points to SUSY being in the decoupling limit. We note in passing that the experimental value of

$Br(B_s^0 \rightarrow \mu^+ \mu^-)$ puts important constraints on dark matter (see Refs. [84, 87]). However, even when m_0 is large one may still have many sparticles which are light, such as the stops, the gluino, the chargino, and the neutralino [14]. The sparticle masses are also susceptible to CP phases (for a review see [88]).

More recently an idea called natural SUSY has been discussed. There are various versions of this idea, but in general terms it implies that the particles that enter in the Higgs loops should be light while others could be heavy. Now the set of particles that participate in the Higgs boson loops are $(\tilde{t}_L, \tilde{b}_L), \tilde{t}_R, \tilde{H}_2, \tilde{H}_1$. Thus specifically one requires that the stops be light and they could be as light as ~ 200 GeV and thus could have been missed in LHC analyses. It is certainly worthwhile to pursue possible signatures for such low mass sparticle and strategies to this effect have been discussed in several works, see, e.g., Refs. [89, 90]. Finally, often EWSB fine tuning criteria are used to favor low scale SUSY. However, such criteria may be unrealistic since there are many other sectors where fine tunings also enter such as in the flavor sector and a more comprehensive approach is needed to include them [91]. Inclusion of these constraints tends to favor the SUSY scale in the TeV region.

The anomalous magnetic moment of the muon provides an important constraint on models. In the Standard Model the electroweak correction to $a_\mu = (g_\mu - 2)/2$ arises from the exchange of the W and of the Z boson and is estimated to be $\delta a_\mu = (28.7 \pm 8.0) \times 10^{-10}$ (using e^+e^- annihilation to estimate the hadronic error) which is 3.6σ excess over the Standard Model prediction and is $\delta a_\mu = (19.5 \pm 8.3) \times 10^{-10}$ [92, 93]. (using the τ decay data to estimate the hadronic error) which is a 2.4σ excess over the Standard Model value. A more recent estimate which includes a tenth-order QED contribution [94] and uses the hadronic error analysis based on e^+e^- annihilation gives $\delta a_\mu = 24.9(8.7) \times 10^{-10}$ which is a three 2.9σ excess over the Standard Model prediction. Now supersymmetry gives contributions to the $g_\mu - 2$ via the exchange of the charginos and sneutrinos and via the exchange of neutralinos and smuons [95, 96]. If the scalar masses are high, the SUSY correction tends to be small and thus the experiment produces a tension between theory and experiment. However, it is known that two loop corrections are significant and could reduce this tension [97]. Alternately, there could be F term or D term corrections to the Higgs boson mass [98–104] thus reducing the need for a large SUSY loop correction which alleviates the tension.

III. SUPERSYMMETRY AND ASYMMETRIC DARK MATTER

An interesting idea concerns cosmic coincidence which relates to the fact that [105] $\frac{\Omega_{DM} h_0^2}{\Omega_B h_0^2} = 4.99 \pm 0.20$, where $\Omega_B h_0^2$ is the relic density of baryonic matter and $\Omega_{DM} h_0^2$ is the dark matter relic density. The fact that the ratio is $O(1)$ implies that perhaps there is a common origin to these two components (for a review see [106]). There is a suggestion that dark matter originates from the transfer of $B - L$ from the visible sector to dark sector in the early universe (For a recent work see [107]). There are two main elements that such an idea involves. The first is that one needs a mechanism for the transfer of $B - L$ from the visible sector to the dark sector. The second is that the dark matter that is produced thermally is dissipated and does not contribute to the total dark matter density. Various mechanisms have been discussed for the transfer and are mentioned in [108]. One example is the interaction $L_{transfer} = M^{-3} \psi^3 L H$ where ψ is the dark matter particle which carries a lepton number and thus a non-vanishing $B - L$. Using the constraints of thermal equilibrium in the early universe [109, 110] one can compute the ratio n_X/n_B where n_X is the number of dark matter particles and n_B is the number of baryons which allows one to compute the ratio of the relic densities of dark matter to baryons, i.e., the ratio Ω_{DM}/Ω_B .

The second issue concerns how one may dissipate the dark matter that is thermally produced. In order to accomplish this we use the Stueckelberg mechanism [111–115] where by the dark particles that are thermally produced can annihilate into the Standard Model particles via a direct channel Z' pole. The Z' corresponds to a gauged $U(1)_X$ symmetry, where for $U(1)_X$ we choose $U(1)_{B-L}$. In this case annihilation of the thermally produced dark matter via the Breit-Wigner Z' boson can completely dissipate the thermally produced dark matter. For the supersymmetric case one has in this picture two dark matter particles: the neutralino and the $B - L$ carrying X particle. In order for the cosmic coincidence to work one must have most of the dark matter, i.e., about 90%, constituted of X, while the remainder can be neutralino. It is then interesting to ask if the neutrino which would have only about say 10% of the total relic density of dark matter could be observed in dark matter experiments. It turns out that indeed this is the case and the neutralino can still be detected in the current direct detection experiments [116–119] and in future experiments such as XENON-1T [120] and SuperCDMS-1T [121]. We note in passing that an interesting recent idea is the so called dynamical dark matter which is constituted of an ensemble of different particle species consisting of different masses and abundances rather than of one type. Interesting implications of such ideas have been discussed in [122, 123].

IV. SUPERSYMMETRY AND UNIFICATION

Grand unified models typically have two problems: the first concerns the fact that in GUT models such as $SO(10)$ many Higgs boson fields are involved in the breaking of the GUT symmetry and one has to adjust the VEVs so that the breakings occurs close to each other and one has the SM gauge group unifying at one scale. This is specifically true of the $SO(10)$ model on which we focus here. Thus, in $SO(10)$ $16 + \bar{16}$ or $126 + \bar{126}$ is used for rank reduction, and one uses 45, 54 or 210 for breaking the symmetry down to the standard model gauge symmetry. Further, for the electroweak symmetry breaking one uses 10 plets of Higgs fields. It turns out that one can replace the above array of Higgs fields by $144 + \bar{144}$ which can break the $SO(10)$ gauge symmetry down to $SU(3)_C \times U(1)_{em}$ [124, 125]. The textures in this class of models are different than in conventional $SO(10)$ models (see, e.g., Ref. [126]). One interesting feature here [124, 127] is that a large $\tan\beta$ [128] is not needed for $b - t - \tau$ unification in this class of models. Special techniques are needed for the computation of $SO(10)$ couplings which have been developed in Refs. [129–131]. Secondly, as is well known, grand unified models have a doublet-triplet problem, i.e., how to make all the color Higgs triplets heavy and one pair of Higgs doublets light. One method used is the so called missing partner mechanism which has been implemented in $SU(5)$ in [132, 133]. The extension of the missing partner mechanism to $SO(10)$ was done more recently and four different cases have been identified [134, 135]. The phenomenology of these models needs to be further worked out.

We discuss now briefly the current status of proton stability. In supersymmetric theories proton decay can occur via dimension 4, dimension 5 and dimension 6 operators (for reviews see Refs. [136–138]). Dimension 4 operators must be forbidden because they give too rapid a proton decay and this can be accomplished by R parity conservation. Dimension six operators arise from the exchange of vector lepto-quarks and the dominant decay mode here is $p \rightarrow e^+ \pi^0$. Proton decay modes can allow one to discriminate between GUTs and strings [139]. Specifically the mode $p \rightarrow e^+ \pi^0$ can allow one, in principle, to distinguish between GUT models and D brane models [140, 141]. The current limit from Superkamiokande for this mode is [143] $\tau(p \rightarrow e^+ \pi^0) > 1.4 \times 10^{34}$ yrs and it is expected that in the future at Hyper-K one will be able to achieve a sensitivity [143] of $\tau(p \rightarrow e^+ \pi^0) > 1 \times 10^{35}$ yrs. This brings one to the edge of observability since unified models predict a decay lifetime which is typically $10^{36 \pm 1}$ yrs.

Proton decay from dimension five operators is the most model dependent. Typically GUT models give too rapid a proton decay and one needs either mass suppression due to the SUSY model being located on the Hyperbolic Branch of radiative breaking of the electroweak symmetry [70] or a cancellation mechanism [142] where $B\&L$ violating dimension five operators from various sources tend to cancel. Proton decay is also sensitive to CP phases [88]. The current experimental situation is as follows: Super-K gives the limit $\tau(p \rightarrow \bar{\nu} K^+) > 4 \times 10^{33}$ yrs, while Hyper-K in the future will reach a sensitivity of $\tau(p \rightarrow \bar{\nu} K^+) > 2 \times 10^{34}$ yrs. It is important to keep in mind that dimension 5 proton decay is very sensitive to the sparticle spectrum and thus observation of sparticles and the measurement of their masses would make the proton lifetime from dimension five operators much more predictive.

V. STUECKELBERG EXTENSIONS

The Stueckelberg mechanism allows generation of mass for a vector boson which is a $U(1)$ gauge field without the necessity of a Higgs mechanism. The Stueckelberg mechanism arises quite naturally in compactification of extra dimensions and in string models where it is directly connected with the Green-Schwarz anomaly cancellation term. While the Stueckelberg mechanism had been around for a long time, its application to particle physics was made only recently [113, 144] where $U(1)_X$ extensions ($U(1)_X$ is a hidden sector gauge symmetry) of the standard model and of MSSM were given. Since then numerous applications of these have been made [111, 113, 114, 144–147] (for related works see, e.g., [148, 149]). These applications arise largely because of the mixing between $U(1)_X$ and $U(1)_Y$ of the standard model which allows the hidden sector to communicate with the visible sector. The DØ Collaboration [150] and the CMS detector Collaboration [151] have put new limits on this class of models. The Stueckelberg mechanism has found many applications such as in the explanation of the PAMELA anomaly, in the dijet anomaly and in protecting [152] R parity against violations due to RG running [153].

VI. CONCLUSION

The observation by ATLAS and CMS of a boson of mass around 125 GeV, has important implications for physics beyond the standard model especially supersymmetry. Although the properties of the new boson still need to be fully established, it is the general perception that the observed particle is indeed the long sought after Higgs boson that

enters in the electroweak symmetry breaking. While in the Standard Model this boson could have a mass over a rather wide range, in supersymmetry it has an upper limit of about 150 GeV. Specifically, in mSUGRA the mass of the Higgs boson is predicted to lie below 130 GeV. It is rather interesting that the observed boson turns out to have a mass which does lie below this limit. An interesting issue for further exploration concerns the nature of the sparticle landscape [154–156] under the 125 GeV Higgs boson constraint. Further, it is now imperative that one explore the implications of this constraint on the allowed parameter space of SUSY, string and D brane models and identify the lightest sparticles that lie within reach of the upgraded LHC. In summary, the observation of the boson, assuming it is the Higgs boson, provides strong support for supersymmetry as it is within the framework of supersymmetry that that an elementary spin zero Higgs boson has a natural setting. Thus the focus of the LHC now must turn to the discovery of supersymmetry in the next round of experiments.

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